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Multiscale characterization of physical, chemical, and mechanical heterogeneity of mudstones

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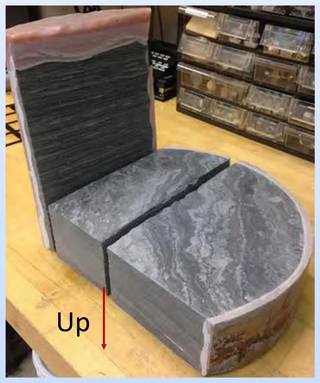
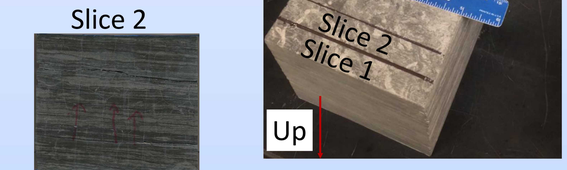
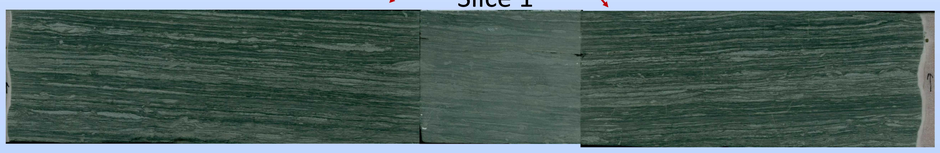
Macroscopic Lithofacies



Mancos Shale block

A block cut from the quarry (left photo).
All thin sections from slice 1 , slice 2 for micropillar tests, and the rest of them for 1-2” cores.

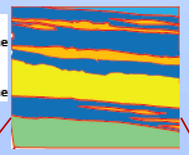




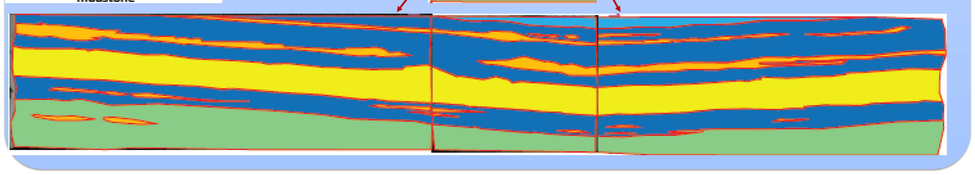
External scan images of the block cut corresponding to the upper right photo

Classification of macroscopic lithofacies

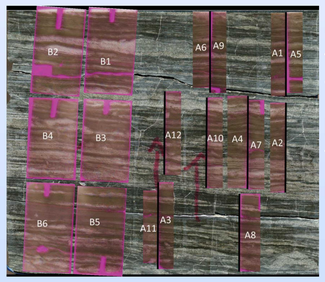
- Interlaminated clay and silt mudstone
- Disrupted very fine sand, silt, and clay mudstone
- Parallel and ripple laminated very fine sand and silt, and clay mudstone
- Lenticular very fine sand and silt sandstone
- Parallel and ripple laminated very fine sand and silt sandstone



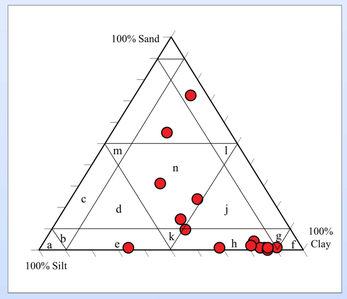
Macroscopic lithofacies Interpretation (observed with hand lense and spray bottle)



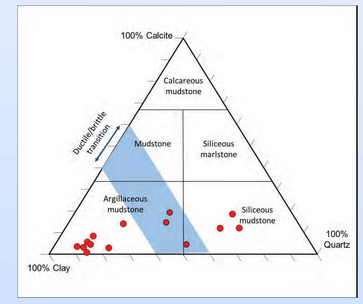
Microscopic Lithofacies: Optical Petrography



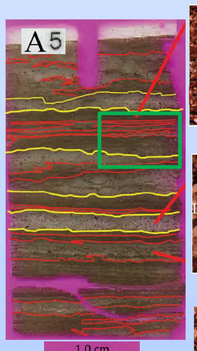
Locations of thin section cut from slice 1 (image=slice2). Thin sections A1-A12 were cut perpendicular to slice 1 and thin sections B1-B6 were cut parallel to the slice.

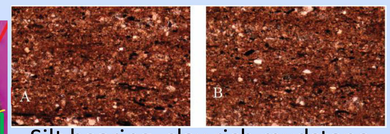


Ternary diagram of compositions of sand, silt and clay sized materials
Classification from Macquaker and Adams (2003).

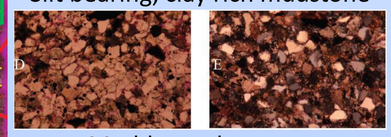


Results of compositions (thin section A5) in a ternary diagram with quartz, calcite, and clay
Classification from Ulmer-Scholle et al.(2014)

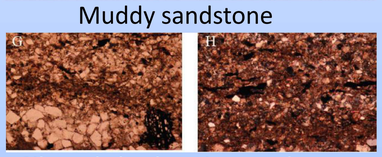




Silt bearing, clay rich mudstone



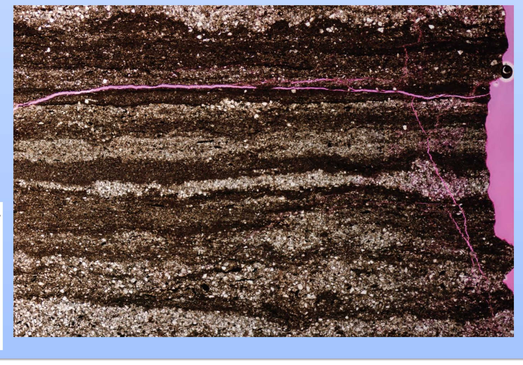
Muddy sandstone

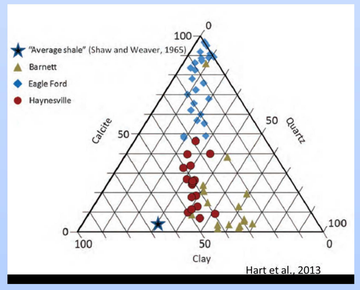


Silt and clay bearing mudstone

- Clay-rich mudstones
- Silt-bearing, clay rich mudstone
- Silt and clay-bearing mudstone
- Clay-bearing, silt rich mudstone
- Sand and silt-baring, clay-rich mudstone
- Sand, silt, and clay baring mudstone
- Muddy, very fine sandstones

Thin section A5 with a blowup of silt-bearing, clay rich mudstone. This lithofacies shows high internal heterogeneity which is expressed by sub millimeter interlaminated silt, clay, and mixed silt and clay.





Various shale samples in a ternary diagram of compositions

X-ray microprobe and QEMSCAN analysis for thin-sections

Multiscale Imaging for pore morphology and mineralogy

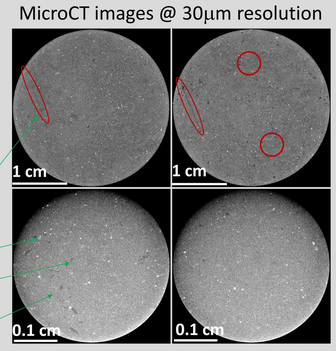
Multiscale Micro-Computed Tomography

- For a small core sample (~ 1” diameter) micro-CT imaging can be obtained at multiple levels
- 3D images are obtained at 1-30 micron resolutions

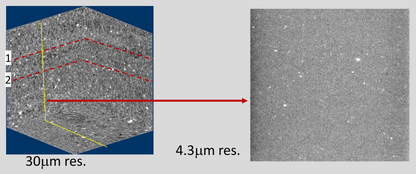
Characterization of pore structures, compositional distribution, surface properties (fluorescence microscopy, microCT, FIB-SEM, TEM, EDS)

1 inch core
Fracture
Grain (white)
Pore & Kerogen (Dark gray)
Matrix

MicroCT images @ 30μm resolution



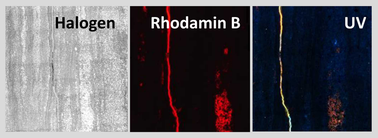
MicroCT images @ 4.3μm resolution



30μm res.

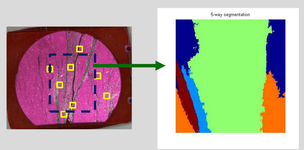
4.3μm res.

Optical & Confocal Microscopy

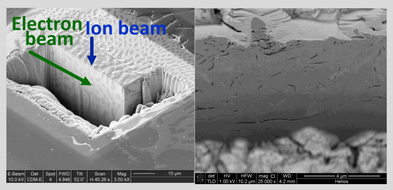


Microfacies by Texture Segmentation

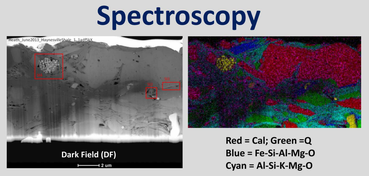
- Fluorescence detection of fluorochromes impregnated in nanopores
- Spectral segmentation with feature identification
- Used as a basis for FIB/SEM sampling
- Fast route to upscaling using multiple point simulation

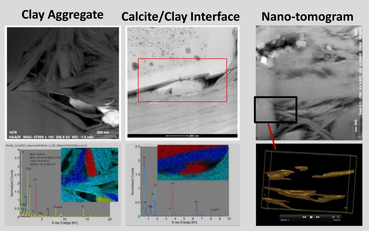


Focused Ion Beam-Scanning Electron Microscopy



STEM-Energy-Dispersive X-ray Spectroscopy

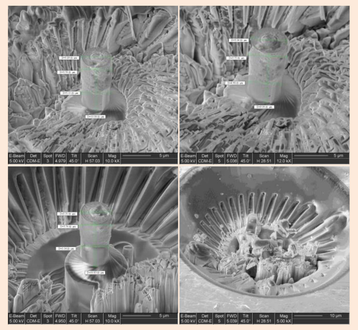


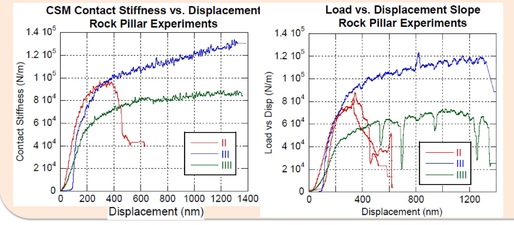


Poro-mechanical Testing

Micropillar Compression Testing

- Focused Ga+ Ion Milling and SEM imaging , including pillar machining and slice-and-view
- Micropillar compression performed with a Hysitron Performech Triboscan Nanoindenter and flat diamond indenter





Triaxial Core Holder Pressure System

- Fullam 1-ton compression/tension load frame
- Core Labs coreholders with sonic velocity, acoustic and X-ray CT imaging capability (15,000 psi and 150°C)
- Associated pressure systems for petrophysics measurements (cap pressure, rel perm etc.)
- Research code for automatic picking of arrival events from acoustic emissions

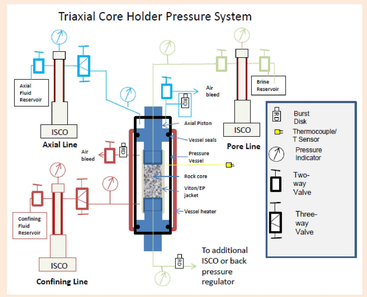


Table 1. Comparison of testing results

	UCS (GPa)	E (GPa)
Pillar II	1.1	29
Pillar III	3.8	37
Pillar IV	6.3	44
Quartz single crystal	6.9-8.3 [8]	76-97
Shale core plug sample	0.088	18

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